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Rainfall patterns and critical values associated with landslides in Povoação County (São Miguel Island, Azores): relationships with the North Atlantic Oscillation

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Abstract:

São Miguel Island (Azores) has been affected by hundreds of destructive landslide episodes in the last five centuries, triggered either by earthquakes, volcanic eruptions or rainfall episodes, which were responsible for many deaths and very important economic losses.

Among the instability causes, meteorological factors are of primary importance on Povoação County, namely the high recurrence rate of calamitous rainfall triggering landslides. The most recent catastrophic episode took place on the 31st October 1997 when almost 1000 soil slips and debris flows were triggered, and 29 people died in the Ribeira Quente village.

The role of rainfall on regional landslide activity was analysed applying cumulative rainfall methods. The method comprises the reconstruction of both absolute and calibrated antecedent rainfalls associated with each major landslide event. The critical rainfall combination (amount-duration) responsible for each landslide event was assessed and a rainfall critical threshold for landslide occurrence was calculated. Rainfall-triggered landslides in the study area are ruled by the function $I = 144{\cdot}06\ D^{-0{\cdot}5551}$, and they are related both to short duration precipitation events (1–3 days) with high average intensity (between 78 and 144 mm/day) and long-lasting rainfall episodes (1–5 months) with a lower intensity (between 9 and 22 mm/day).

The impact of the North Atlantic Oscillation (NAO) on the regional precipitation regime was evaluated. It is shown that the monthly precipitation of São Miguel is largely modulated by the NAO mode presenting a significant negative correlation with the NAO index. This result arises from the NAO control on the travelling latitude of most storm tracks that cross the Northern Atlantic Ocean.

KEY WORDS landslides; rainfall patterns; North Atlantic Oscilation; São Miguel; Azores

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INTRODUCTION

Portugal is a country particularly prone to slope instability due to geological, geomorphologic and climatic factors (Rodrigues and Coelho, 1989; Ferreira and Zêzere, 1997; Zêzere *et al*., 2005). Despite the associated economic losses, the majority of landslide events do not cause human casualties. However, in the last decade, episodes of shallow slope movements in the Azores archipelago and in the northern continental Portugal were directly responsible for the loss of more than 40 human lives (33 of which in Povoação County, São Miguel, Azores). Landslide episodes in mainland, particularly near Lisbon, have been characterized comprehensively over the last two decades (Zêzere *et al*., 1999a, b; Zêzere, 2000; Zêzere and Rodrigues, 2002; Zêzere *et al*., 2005; Trigo *et al*., 2005). However, the hazard and main characteristics of landslide events in the Azores archipelago have only recently started to be addressed by the scientific community and are restricted to the main Island of São Miguel (Valadão, 2002; Valadão *et al*., 2002; Marques, 2004). These studies were motivated by the catastrophic event of October 31, 1997, when nearly 1000 shallow slope movements (mainly of debris-flow type) were triggered by heavy rainfall. This catastrophic event claimed 29 human lives, and 36 houses were destroyed and 114 residents were left homeless, and the village of Ribeira Quente was isolated for more that 12 h (Gaspar *et al*., 1997; Marques, 2004). Communication, transportation and the energy supply system were disrupted and areas of fertile land became covered by mud. The total financial loss was estimated at €21 300 000 including both direct and indirect damages (Cunha, 2003).

There are various factors affecting slope stability and some of them are closely related. Among instability causes, meteorological factors are of primary importance, namely, the control exerted on the amount of available water for infiltration into soils and rocks. Meteorological and climate factors may act as pre-disposing factors

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within the slope instability system, but more frequently they represent the ultimate cause, or the triggering factor, of landslide activity (Fukuota, 1980; Crozier, 1986; Wieczorek, 1996; Corominas, 2001).

The influence of rainfall on landslides differs substantially depending upon landslide dimensions, kinematics, material involved, etc. Shallow slope movements are usually triggered by short, intense storms (Campbell, 1975; Lumb, 1975; Cannon and Ellen, 1985; Wieczorek, 1987; Polloni *et al.*, 1992; Crosta, 1998; Flentje *et al.*, 2000; Zêzere and Rodrigues, 2002; Paronuzzi *et al.*, 2002), while most deep-seated landslides are usually related with rainfall periods lasting from several weeks to several months (Brunsden, 1984; Polemio and Sdao, 1999; van Asch *et al.*, 1999; Bonnard and Noverraz, 2001; Zêzere and Rodrigues, 2002; Trigo *et al.*, 2005). The physical explanation of these different behaviours is probably related to infiltration processes, namely the different pressure head responses to rainfall controlled by soil characteristics, slip surface depths and effective hydraulic diffusivities (Iverson, 2000). The existence of different hydrological triggering mechanisms, related to different types of landslides, does not allow the definition of an empirically based universal rainfall threshold that can be associated with landslides (Dikau and Schrott, 1999; Corominas, 2001).

Several destructive landslides have affected São Miguel, the largest and most populated island of the Azores archipelago, in the last five centuries, triggered either by earthquakes, volcanic eruptions or rainfall episodes: or maybe by an accidental combination of these triggering factors. Some of these episodes were responsible for many deaths and very important economic losses. In this Island, and in particular for our study area of Povoação County, the vast majority of landslides have been triggered by intense rainfall events. Consequently, the study of appropriate rainfall conditions responsible for landslide episodes that occurred in the past is of outmost relevance for future land use and emergency planning.

A comprehensive description of the precipitation regime at the regional (Azores archipelago) and local (Povoação County) scales is proposed here. In particular the inter-annual variability of precipitation is examined to understand the temporal variation of landslide activity and to define rainfall patterns and critical rainfall values responsible for landslide occurrence. In recent years, it has been clearly shown that the winter precipitation in southern Europe, particularly for the western Iberia sector, is clearly associated with the North Atlantic Oscillation (NAO) mode of atmospheric circulation variability (Hurrell, 1995; Corte-Real *et al.*, 1998; Trigo *et al.*, 2004a). The NAO corresponds to the most important large-scale mode of atmospheric circulation in the winter season over the entire Northern Hemisphere (Barnston and Livezey, 1987; Hurrell, 1995). In fact, this is the only atmospheric circulation mode that is present throughout the year, although it is especially prominent in winter (Barnston and Livezey, 1987). Moreover, its impact on the climate of Europe (and the entire North Atlantic basin) is very important (Qian *et al.*, 2000; Trigo *et al.*, 2002, 2004a), unlike the El Niño episodes that have almost no impact in this region. This control exerted by the NAO on the precipitation field is related to corresponding changes in the associated activity of the North Atlantic storm tracks (Osborn *et al.*, 1999; Ulbrich *et al.*, 1999; Trigo *et al.*, 2002; Zêzere *et al.*, 2005).

Recent works have been able to establish the links between landslide activity and low-frequency atmospheric circulation patterns such as the El Niño episodes for different locations on the Pacific basin (Coe *et al.*, 1998; Godt, 1999). Likewise, Trigo *et al.* (2005) and Zêzere *et al.* (2005) have found a significant control exerted by NAO on the Portuguese mainland precipitation and over the recent geomorphological activity in the area around Lisbon.

Therefore, the main objectives of this study are: (1) to describe the main characteristics of episodes of landslide activity observed from 1936 to 2002 in Povoação County, São Miguel Island, Azores; (2) to discriminate precipitation events (amount/duration) responsible for landslide activity using empirical methodologies; (3) to define an empirical rainfall threshold associated with local landslides; and (4) to characterize the impact of NAO on the location of cyclones that strike Azores, as well on the precipitation regime at the large (Atlantic basin) and local (Povoação County) scales and, eventually on the occurrence of landslide episodes.

STUDY AREA AND LANDSLIDE INCIDENCE

The Azores archipelago is situated in the North Atlantic Ocean (Figure 1(a)) where the American, African and Eurasian lithospheric plates meet. Because of its tectonic setting, both seismic and volcanic events are frequent in the Azores archipelago. Nevertheless, landslides are the most common type of geological hazard, being conditioned by the volcanic constitution and morphology of the islands, namely, the presence of steep slopes developed on incoherent materials. The human settlement in the Azores islands started in early 15th century, and since then several destructive landslides occurred, triggered usually by catastrophic rainfall episodes (e.g. October 31, 1997, described by Gaspar *et al.*, 1997; Valadão, 2002; Marques, 2004) but also by earthquakes (e.g. October 22, 1522, described by Marques, 2004) and volcanic eruptions (e.g. September 3, 1630). São Miguel Island is the most populated island, and is located in the eastern segment of the so-called Terceira Rift (TR; Figure 1(b)). The island is characterized by a large variety of volcanic structures, including three active trachytic composite volcanoes with caldera (Sete Cidades, Fogo and Furnas, Figure 2), emplaced in the intersection of the NW–SE to WNW–ESE regional faults with an E–W deep fault system, thought to be a relic of the Mid-Atlantic Ridge (MAR; Figure 1) transform fault (Queiroz, 1997). N–S and NE–SW faults also occur in this context. Trends of basaltic

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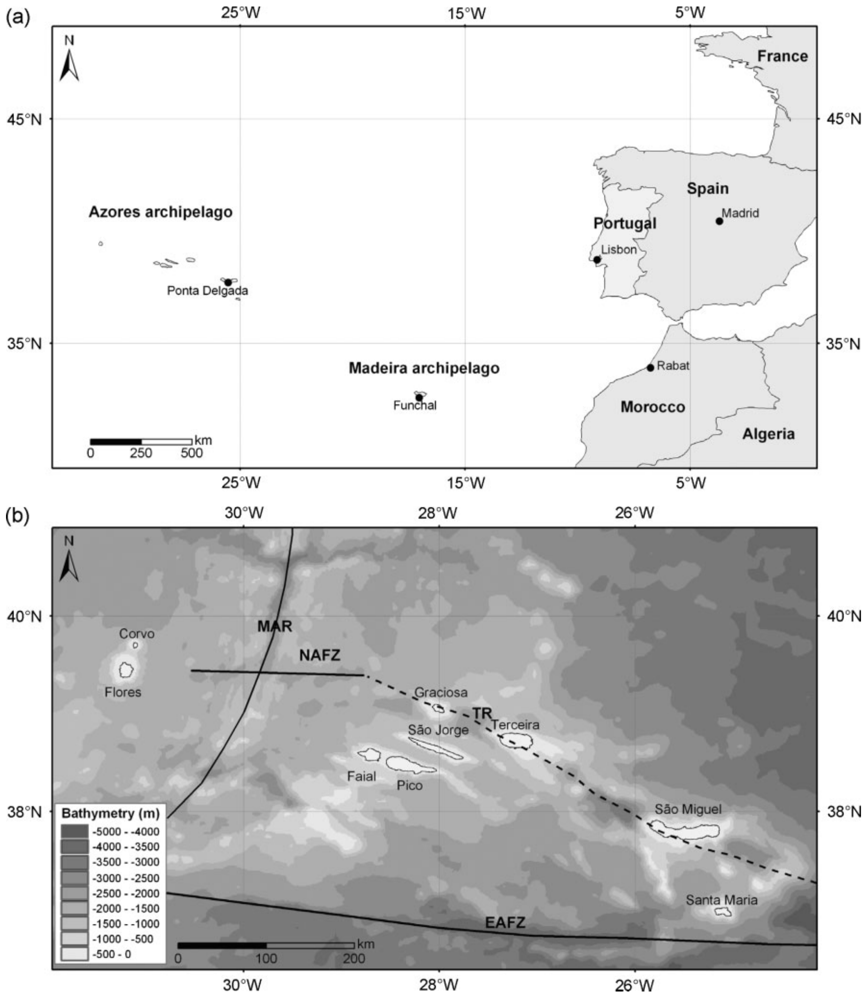

Figure 1. (a) Location map of the Azores archipelago and (b) main tectonic structures map of the Azores archipelago. Bathymetry from Lourenço *et al*. (1998). Legend: MAR—Mid-Atlantic Ridge; NAFZ—North Azores Fracture Zone; EAFZ—East Azores Fracture Zone and TR—Terceira Rift

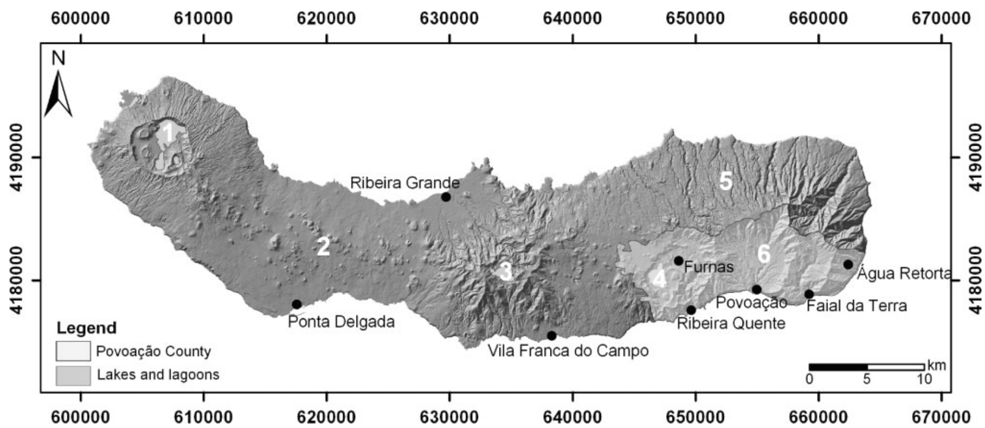

Figure 2. Geomorphologic units of São Miguel Island. Legend: 1—Sete Cidades Volcano; 2—Picos Region; 3—Fogo Volcano; 4—Furnas Volcano; 5—Povoação Volcano and 6—Nordeste Volcanic Region

cinder cones link those major volcanic structures along NW–SE to WNW–ESE fractures. The eastern part of the island comprises an inactive trachytic composite volcano (Povoação) and an old basaltic volcanic complex (Nordeste).

The present study focuses on Povoação County (area of 106 km^2), which is located in the south-eastern part of São Miguel Island (Figure 2). Like many other active volcanic regions in the world, Povoação County is characterized by deep streamlines and very steep slopes (Figure 3(b)). In the Northern sector, there is an E–W alignment of peaks where is located the highest point of the island (1103 m, Figure 3(a)). The southern sector of the study area is limited by a very steep

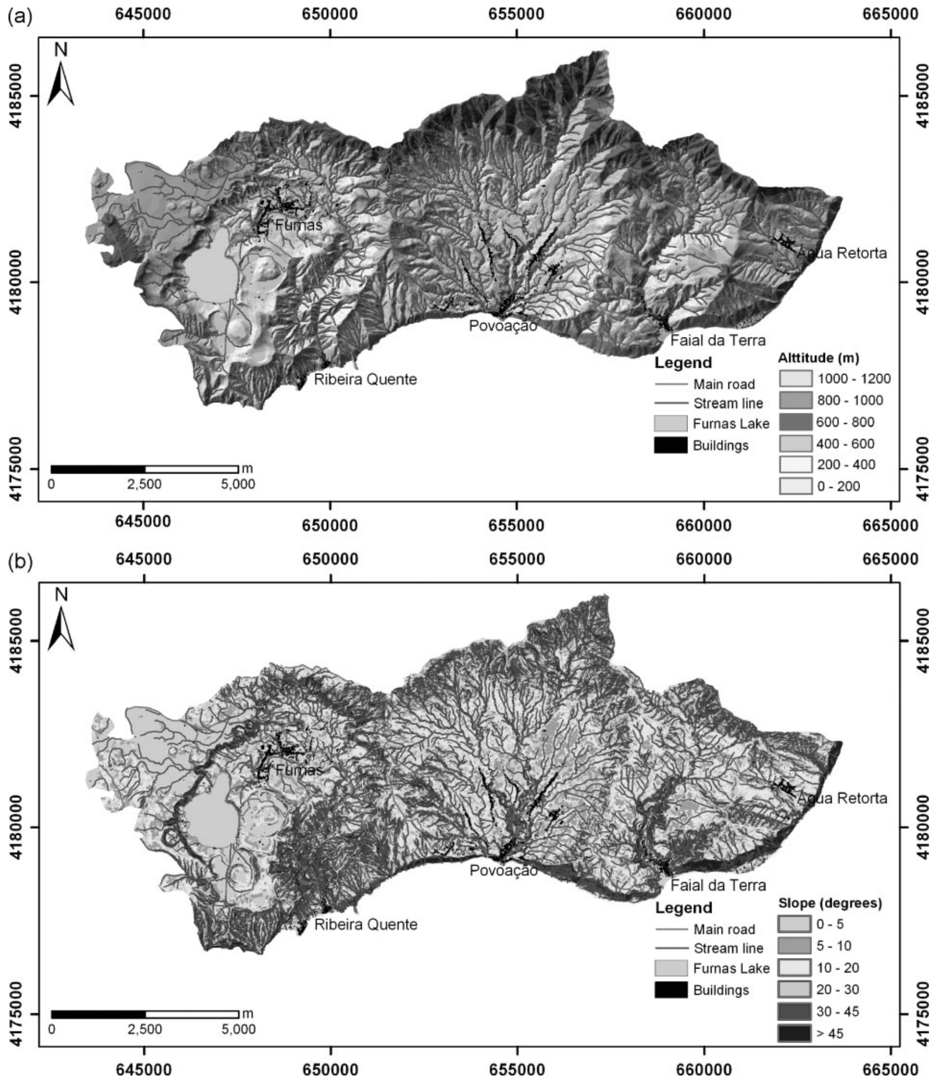

Figure 3. Povoação County thematic maps: (a) hypsometric map and (b) slope map

coast line dominated by sea cliffs frequently higher than 400 m (Figure 3(a)). The county includes two different volcanic edifices, Furnas and Povoação (Figure 2). The calderas associated with these volcanoes have a strong expression on the geomorphology of the county, namely, on configuration of the fluvial system. Within these two polygenetic volcanoes the fluvial channels are very dense and deeply fitted (Figure 3). The small fluvial channels have a typical torrential regime with a huge destructive potential, and so they are highly prone to flash flood generation. This is an important source of risk since the hazardous alluvial fans corresponding to the main rivers (Ribeira Quente, Ribeira da Vila and Faial da Terra rivers) are densely urbanized by the most important villages of the county.

From the geological point of view, the study area is composed of unconsolidated pyroclastic deposits from recent explosive eruptions (fall-out deposits) and permeable soft volcanic soils, characterized by very low values for resistant parameters (cohesion and friction angle). Additionally, the stratification and fracturation index, observed in some deposits, induce large values of permeability that favour an intense circulation of water. Water infiltration contributes to instability of slopes both indirectly through the weathering of rocks and soils (reduction of the resistant parameters), and directly through the increase of the pore pressure.

Morphological and lithological characteristics make Povoação County one of the Azores landslide-prone zones (Gaspar *et al*., 1997; Marques, 2004), which is confirmed by a very high landslide density (Figure 4), related to the young central volcanoes and sea cliffs in their vicinity. Most of these landslides (almost 1000) were triggered during the catastrophic episode that occurred in October 1997 (Figure 5).

Landslide activity verified in 1997 was characterized by the widespread development of shallow translational slides (soil slips) evolving downslope into very fluid debris flows (Figure 5(a) and (b)). The vast majority of landslides originated near the crest of very steep slopes and spread over the complete length of the slope. Soil slips are narrow (landslide width ranging typically from 20 to 30 m), and the depth of the planar slip surface does not surpass 2–3 m. Shallow translational slides affected

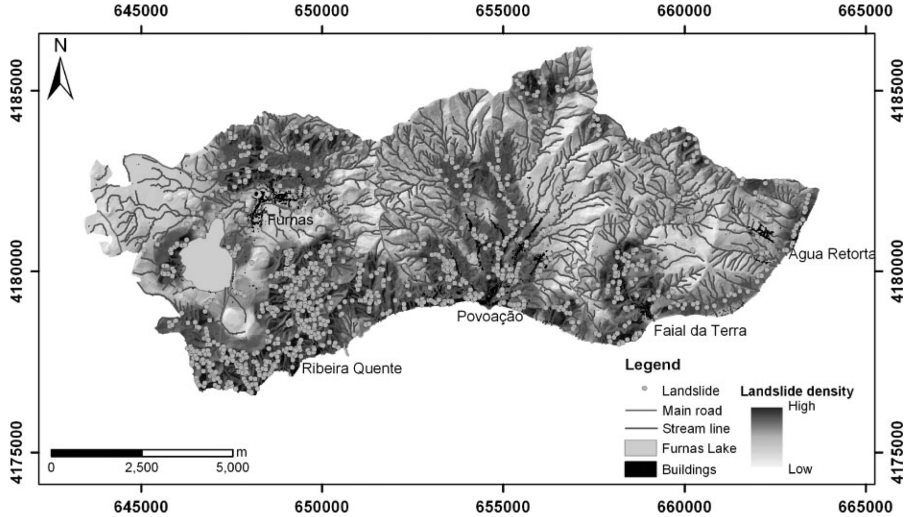

Figure 4. Povoação County landslide density map (after Valadão, 2002 and Marques, 2004)

mostly unconsolidated pyroclastic deposits and permeable soft volcanic soils. These landslides occurred in thickly vegetated slopes, namely by *Hedychium gardneranum* (an invasive species that grow in almost all island) and *Cryptomeria japonica* (a common tree on the island). These species are shallow rooted and do not provide a significant increase in soil strength by root reinforcement and by the buttressing and soil arching between plants. Therefore, the existing vegetation cover is not effective in preventing shallow slope movements, but endorses the infiltration of surface water leading to a more rapid and thorough saturation of the soil mantle, thereby promoting soil failure. Additionally, during rainstorms characterized by strong winds, *C. japonica* root system can be uprooted; such uprooting will contribute to trigger larger slope failures and to increase the volume of the disrupted mass (Gaspar *et al*., 1997; Marques, 2004; Malheiro, 2006).

Velocity of soil slips is usually very rapid (3 m/min to 3 m/s) within the study area, owing to the high relief energy and the high water content of the affected materials. Therefore, the disrupted material moves outside the rupture area, and evolves downslope into very rapid debris flows. These debris-flows consist of a low-viscosity mixture of water, pumice and ash, which flows at high velocity along the slopes and the fluvial channels (Figure 5). The flowing mass also includes trees with their root systems, tree trunks and branches. Depending on the source, some debris-flows also include large blocks of lava (Gaspar *et al*., 1997) (Figure 5(e)). Such solid charge promotes the erosive capacity and the very high destructive power that characterize debris flows in the study area (Figure 5(c), (d), (e), (f), (g) and (h)).

RECONSTRUCTION OF THE PAST RAINFALL-TRIGGERED LANDSLIDE EVENTS

The landslide occurrences used in this study were collected from historical accounts, technical-scientific documents, periodical papers (national and regional) and interviewing the local people (Table I). Forty major rainfall episodes that triggered landslides were identified since the beginning of the 20th century, some of them occurring within the same climatological year (from September of year n until August of year $n+1$). Usually, these episodes were dominated by shallow slope movements (SSM), while a minority was marked by the occurrence of deep-seated slope movements (DSSM).

All landslide episodes were classified according to their socioeconomic impact: Minor (M)—when few and isolated landslides occurred, having a negligible socioeconomic impact; Severe (S)—when landslides had an important socioeconomic impact; and Disastrous (D)—when landslides occurred with an extensive geographic dispersion and have caused victims and/or had a large socioeconomic impact. In the selection of these case studies, an effort was made to eliminate those landslide episodes that were probably not triggered by rainfall, but by earthquakes. This selection was performed after matching dates of landslides with known earthquake occurrences, using the earthquake data from the Seismic-Volcanic Warning System of Azores (SIVISA).

RAINFALL ANALYSES AND LANDSLIDE ACTIVITY

Rainfall regime

The altitude and the exposure of the terrain to the dominant winds are important variables that regulate the spatial distribution of the precipitation in the archipelago (Agostinho, 1941; Bettencourt, 1979). Naturally, the large-scale atmospheric circulation also plays an important role in determining the differences of the precipitation regime among the different groups of islands in Azores. Consequently, the annual precipitation values generally grow from the East group (São Miguel and Santa Maria islands) to the West group (Flores and Corvo islands), and are higher in the north coasts of the islands (Agostinho, 1941).

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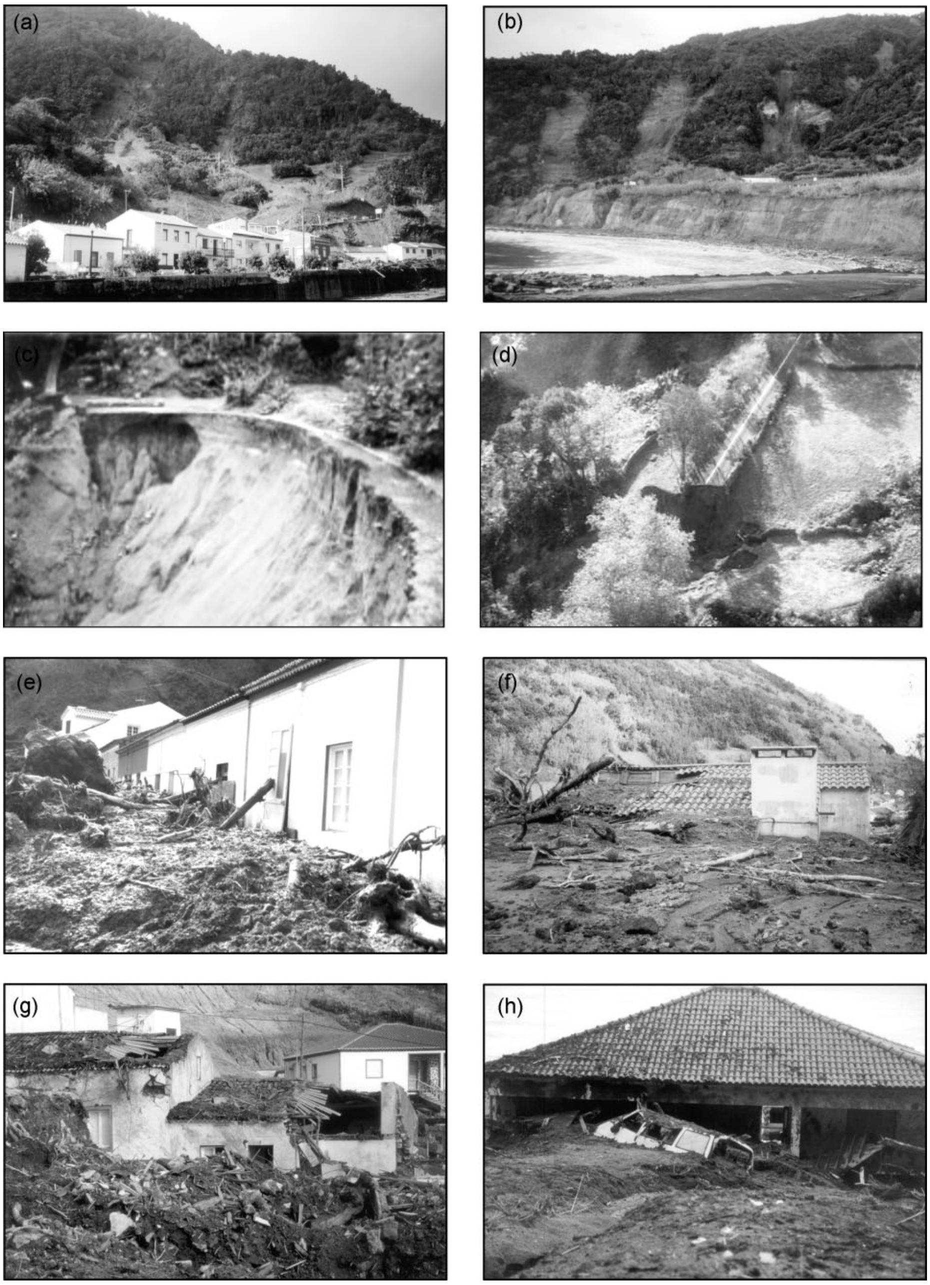

Figure 5. October 31, 1997 landslides and their impact in Ribeira Quente village (Povoação County). Legend: (a and b) General aspect of some of the landslides occurred; (c and d) Roads damaged by deep-seated landslides; (e and f) Roads and houses buried by the landslides deposits; (g and h) Houses and vehicles totally destroyed by the passage of the debris flows. Photos c and d are from Laboratório Regional de Engenharia Civil (LREC)

Rainfall analysis was carried out using 65 climatological years (1936/37–2001/02) of monthly precipitation and 26 climatological years (1976/77–2001/02) of daily precipitation, registered at the reference meteorological station of Lagoa das Furnas (EMLF; Figure 6). This meteorological station has the most complete rainfall data series for the study area, and it is assumed to be representative of Povoação County concerning rainfall regime. The mean annual precipitation (MAP) at EMLF (for this period) is 1992 mm. The precipitation regime is dominated by high variability at both the inter-annual (Figure 7) and inter-seasonal (Figure 8) scales. The monthly rainfall distribution shows an evident seasonal pattern, with a significant difference between the 'rainy season' that extends between October and March, and the 'dry season' with a minimum of rainfall in July (Figure 8). It is worth noting that the seasonal precipitation cycle depicted in Figure 8 was obtained from six rain gauges located within the Povoação County (Figure 6). As expected, the precipitation regime of these stations is in phase, with almost identical timing for maximum and minimum values. However, the magnitude of these extreme values varies significantly, being largely influenced by the altitude of each individual station (Figure 6).

Most landslide events in Povoação County (85% of total events) occurred between October and March, during the wet period of the year. Figure 9 shows the exceptional climatic conditions of some of the observed

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Table I. Rainfall-triggered landslide occurrences in the last 100 years in Povoação County. SSM: Shallow slope movements; DSSM: Deep seated slope movements and FF: Flash floods

ID	Date	SSM	DSSM	FF	Victims	Intensity	Most affected sites
1	1918, Aug. 9	X	—	X	—	S	Furnas (Salto do Fojo)
2	1919, Aug. 9	X	—	X	—	D	Furnas, Ribeira Quente
3	1920, Dec. 31	X	X	—	—	M	Furnas (Salto do Fojo)
4	1924, Mar. 13 or 14	X	—	—	—	M	Povoação
5	1925, Dec. 18	X	—	X	—	S	Povoação
6	1926, Sep. 26	X	—	—	—	S	All the county
7	1928, May 21 to 23	X	—	X (?)	—	S	Ribeira Quente, Povoação
8	1932, Aug. 20	X	—	.	—	M	Povoação
9	1933, Feb. 22	X	—	—	—	M	Between Furnas and Povoação (Rib. Tambores)
10	1934, Oct. 23	X (?)	—	X	—	S	Furnas
11	1934, Nov. 26	X	—	—	—	M	Furnas
12	1938, Feb. 20	X (?)	—	X	—	S	Furnas
13	1939, Nov. 21	—	X	—	—	M	Povoação (Lomba do Carro)
14	1939, Dec. 31	X	—	X	—	S	Povoação
15	1940, Jan. (??)	X	—	—	—	S	Furnas (Salto do Fojo)
16	1940, Aug. (??)	X	—	X	1 (out county)	S	Furnas (Salto do Fojo)
17	1940, Sep. (??)	X	—	X	—	S	Furnas (Salto do Fojo)
18	1941, Jan. 27(?)	X	—	—	—	S	Ribeira Quente
19	1942, Oct. 14	X	X	X	7	D	Furnas (Salto do Fojo)
20	1946, Feb. 23	X	X	X	—	S	Furnas (Salto do Fojo)
21	1948, Oct. 11	X	X	X	—	S	Furnas (Salto do Fojo)
22	1949, Jan. 27(?)	X	X (?)	X	—	S	Furnas (Salto do Fojo)
23	1952, Feb. 27	X	—	—	—	S	Ribeira Quente
24	1968, Dec. 29	X	—	—	—	M	Furnas
25	1969, Mar. 18	X	—	X	—	D	Povoação
26	1980, Apr. 09	X	—	X	—	M	Povoação
27	1981, Feb. 18	X	—	X	—	S	Água Retorta
28	1982, Oct. 7	X	—	—	—	M	Povoação
29	1983, Jan 24(?)	X	—	—	—	S	Povoação
30	1983, Mar. 04	X	—	—	—	M	Povoação
31	1985, Feb. 07	X	—	—	—	S	Povoação
32	1986, Sep. 02	X	—	X	5	D	Povoação, Faial da Terra
33	1996, Apr. 25 to 29	X	X	—	—	S	Furnas (Salto do Fojo)
34	1996, Dec. 14	X	—	X	—	D	Povoação
35	1997, Sep. 10	X	—	X	1	D	Ribeira Quente, Povoação
36	1997, Oct. 31	X	—	X	29	D	Ribeira Quente
37	1998, Jan. 25	X	—	X	—	S	Faial da Terra
38	1998, Oct. 1	X	—	—	—	S	Ribeira Quente, Povoação, Faial da Terra
39	2001, Dec. 18	X	—	—	—	S	Faial da Terra
40	2002, Feb. 12	X	—	X	—	S	Faial da Terra

slope instability events: 25% of the total landslide events (including 80% of the disastrous episodes) are located above the 90 percentile (P90) curve, corresponding to monthly rainfall values that are observed (on average) once per decade. Furthermore, 75% of the slope instability events are above the curve P50 that represents the median monthly rainfall.

Reconstruction of absolute antecedent rainfall

This analysis consists on the computation of the cumulative absolute rainfall for 1, 2, 3, 5, 10, 15, 30, 40, 60, 75, 90, 120 and 150 consecutive days before each major landslide event during the 26 years period (1976/77–2001/02), by applying Equation 1:

$$Px = P_1 + P_2 + \ldots + P_n \tag{1}$$

where Px is the absolute antecedent rainfall for day x; P_1 is the daily rainfall for the day before x; P_n is the daily rainfall for the *nth* day before day x.

The return period of each rainfall amount–duration combinations was computed using the theoretical distribution described by Gumbel (1958), also known as *Fisher–Tippett type I distribution* (Fisher and Tippett, 1928), commonly used for extreme value analyses (Equation 2):

$$F(x_N < x_r) = \exp\{-\exp(-y)\} \tag{2}$$

where x_N is the maximum x from a sample of size N; x_r = a reference value of x_N; $y = \alpha(x_r - u)$, the reduced Gumbel variate; $u = \mu - (c/\alpha)$, the mode of the Gumbel distribution; μ = mean of the Gumbel distribution; c = Euler's constant = 0·577; $\alpha = \pi/(\sigma\sqrt{6})$; σ = the standard deviation of the Gumbel distribution.

This distribution was already used by the authors in previous works, although for different study areas, guaranteeing good fitting results to the local observed extreme value distribution (e.g. Zêzere and Rodrigues,

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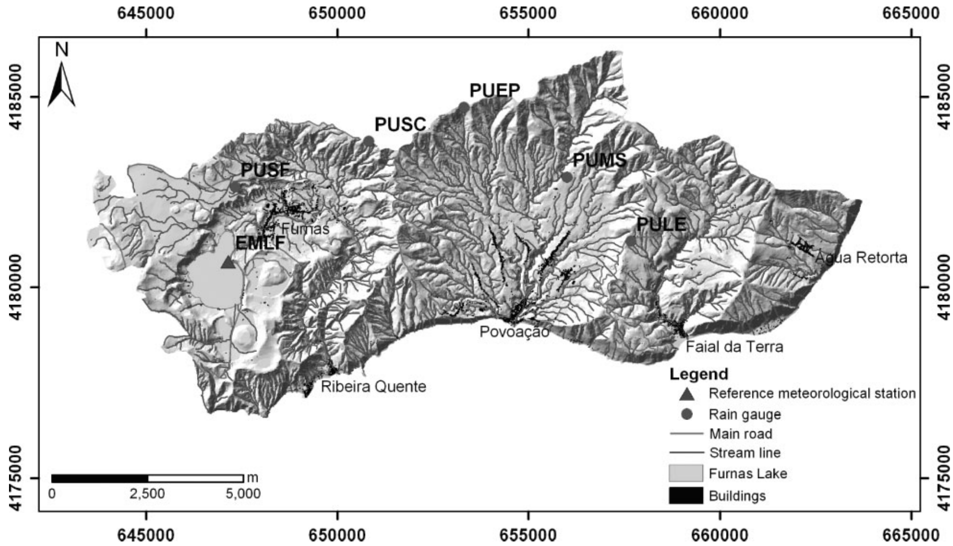

Figure 6. Povoação County reference meteorological station and rain gauges. Legend: EMLF—Lagoa das Furnas meteorological station; PUSC—Salto de Cavalo rain gauge; PUSF—Salto do Fojo rain gauge; PUMS—Monte Simplício rain gauge; PULE—Lomba da Erva rain gauge and PUEP—Espigão da Ponte rain gauge

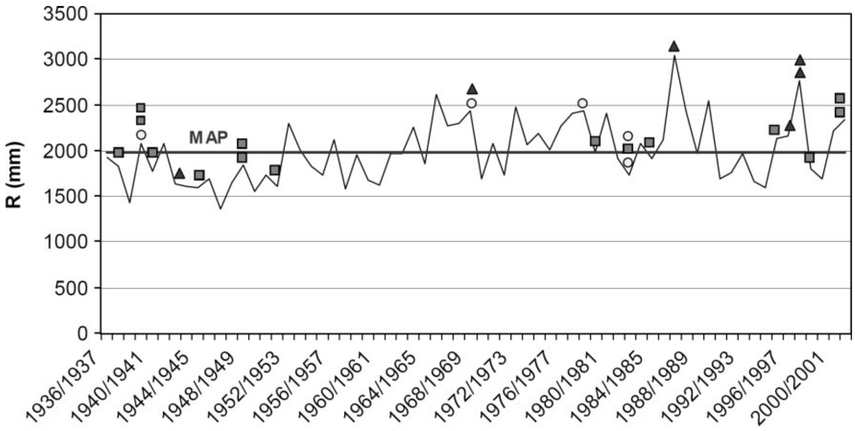

Figure 7. Annual precipitation (climatological year) at Lagoa das Furnas (reference meteorological station) from 1936/37 to 2001/02. Legend: the horizontal line indicates the mean annual precipitation (MAP); triangles indicate disastrous landslide events; squares indicate severe landslide events and circles indicate minor landslide events

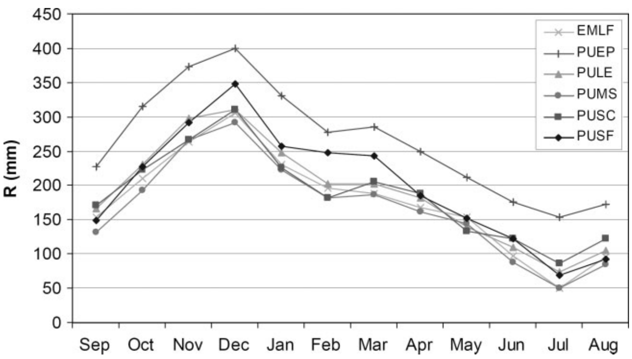

Figure 8. Monthly rainfall average for different rain gauges in Povoação County (1936/37–2001/02). See Figure 2 for location of rain gauges

2002; Marques, 2004; Trigo *et al*., 2005; Zêzere *et al*., 2005).

The critical rainfall combination (amount–duration) responsible for each landslide event was assessed, assuming as critical pair the combination with the higher return period (bold, in Table II). This assumption is not physically based, but provides a maximum discrimination between rainfall periods characterized by landslide activity and rainfall periods not related to slope instability. The rainfall intensity reported in Table II was assessed using the rainfall critical combination (amount–duration) assumed to be responsible for each landslide event (Table II).

Reconstruction of antecedent rainfall was applied only to those events that occurred after the climatological year of 1976/77 (events 26 to 40, in Table I) due to unavailability of daily rainfall data prior to that year. The obtained results for events 27 and 28 were not conclusive because these events were induced by very localized storms affecting only the NE part of Povoação County and, in particular, the contiguous Nordeste County very far away from the reference meteorological station. Therefore, in these cases the precipitation registered in EMLF was not representative of the rainfall verified in the NE corner of the island. Events 37, 39 and 40 affected

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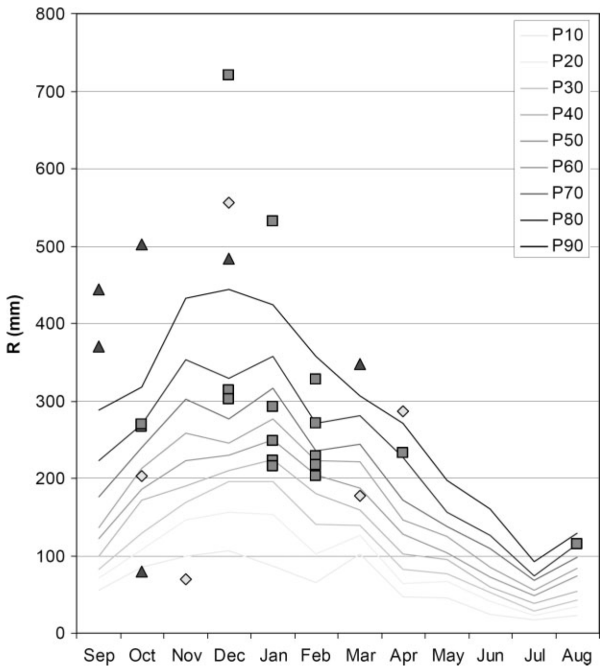

Figure 9. Percentiles of monthly precipitation at Furnas (1936–2002) and landslide events. Legend: triangles indicate disastrous landslide events; squares indicate severe landslide events and circles indicate minor landslide event

mostly the Faial da Terra village, but were spread over the complete study area. Therefore, we consider the rainfall registered in EMLF representative of these events.

Reconstruction of calibrated antecedent rainfall

Effects of a particular rainy event decrease in time owing to drainage processes (Canuti *et al*., 1985; Crozier, 1986). Therefore, in order to account for this dampening effect in the rainfall–landslide analysis, the antecedent rainfall was calibrated applying the formula proposed by Crozier (1986) (Equation 3):

$$CARx_n = KP_1 + K^2P_2 + \ldots + K^nP_n \tag{3}$$

where CAR_x is the calibrated antecedent rainfall for day x; P_1 is the daily rainfall for the day before x; P_n is the daily rainfall for the *nth* day before day x. The constant K is an empirical parameter (typical values range between 0·8 and 0·9) depending on the draining capacity and the hydrological characteristics of the area (Capecchi and Focardi, 1988). After a few tentative trials we decided to assume in this study that $K = 0{\cdot}9$, making negligible precipitation occurred more than 30 days before a landslide event (Capecchi and Focardi, 1988). The reconstruction of calibrated antecedent rainfall was performed for time periods of 3, 5, 10, 15 and 30 days.

Table III summarizes results of calibrated antecedent rainfall for landslide events 26–40. Figure 10 shows the evaluation of the triggering rainfall conditions combining the daily rainfall with the calibrated antecedent rainfall for 5, 15 and 30 days.

Some important landslide events (e.g. event ID37) seem to be related to a two-stage pattern of precipitation: (1) a preparatory rainy period,15 days before the occurrences, when slopes are destabilized and conditioned for failure, followed by (2) a more intense and short rainfall episode (1 or 2 days) that triggers the landslide. The only exception to this rule corresponds to event 33 (Table III) that took place on April 26, 1996. This event was related with a more prolonged rainy period responsible for the reactivation of a deep rotational slip, contrasting with the other events dominated by shallow slope movements.

Rainfall triggering thresholds

As it was shown in Table II, the rainfall conditions that trigger landslides in Povoação County can be very different. If we consider the critical pairs of rainfall amount–duration for all 15 reported landslide events, the regression line that relates rainfall intensity (I) and duration (D) can be plotted (Figure 11). In order to validate this rule as a reliable rainfall triggering threshold, the yearly maximum rainfall for durations of 1, 2, 3, 5, 10, 15, 30, 40, 60, 75, 90, 120 and 150 consecutive days were computed for the years in which no landslide activity was reported, and also plotted in Figure 9 (small black dots). As can be seen, the vast majority of these points fall below the fitted curve. The regression analysis show that rainfall intensity increases exponentially as duration decreases, following the equation $I = 144{\cdot}06\ D^{-0{\cdot}5551}$, where I is the rainfall intensity in mm/day and D is the duration of rainfall in days. Therefore, the regression curve can be considered as a reliable rainfall intensity–duration threshold for the study area, above which, landslide events may occur. However, this rainfall threshold is statistically based and was not defined considering the hydrological response to rainfall of the soil as well as the local slope stability conditions.

Considering only severe and disastrous events, it can be seen that there are two distinct hydrological conditions for their occurrence: (1) intense rainfall episodes in short periods (1–3 days) with high average intensity (between 78 and 144 mm/day) and (2) precipitation accumulated during longer periods (1–5 months) with a lower rainfall intensity (between 9 and 22 mm/day). In the first case, the rainfall intensity required to trigger landslides is highly dependent on the duration of the precipitation event; in contrast, for long-duration precipitation periods (above 30 days) the daily rainfall intensity tends to stabilize around 9–22 mm/day. It can be observed that there is a complete constriction of disastrous landslide events to exceptional, high-intensity rainfall occurrences, which happen very close to the day of the event such as the catastrophic event of October 31,1997 (event 36).

THE IMPACT OF THE NAO ON THE PRECIPITATION AND STORM OCCURRENCE OVER THE AZORES ARCHIPELAGO

The NAO corresponds to the major pattern of extratropical atmospheric variability, accounting for roughly

Table II. Absolute antecedent rainfall from 1 to 150 days and corresponding return period for 15 landslide events verified in Povoação County from 1976 to 2002. R: rainfall (mm); R.P.: return period (years). Critical rainfall amount–durations are highlighted in bold. Rainfall intensity reports to critical rainfall amount–duration

ID	Date		1 day	2 days	3 days	5 days	10 days	15 days	30 days	40 days	60 days	75 days	90 days	120 days	150 days	Rainfall intensity (mm/day)
26	1980 Apr. 09	R (mm)	42·1	105·1	105·1	119·1	139·6	232·6	**393·2**	399·7	548·8	711·7	786·4	882·0	1019·5	13.1
		R.P. (y)	1·01	1·2	1·1	1·04	1·02	1·1	**1·3**	1·009	1·1	1·2	1·2	1·1	1·1	
27	1981 Feb. 18	R (mm)	40·6	66·4	67·7	68·0	128·8	132·4	183·9	193·0	233·2	324·0	688·7	1100·5	**1355·3**	9.0
		R.P. (y)	1·01	1·02	1·01	1·001	1·01	1·001	1·001	1·001	1·001	1·001	1·04	1·5	2	
28	1982 Oct. 7	R (mm)	34·2	34·2	34·2	36·8	47·7	49·6	93·6	102·6	111·8	135·8	232·3	308·5	434·0	Not conclusive
		R.P. (y)	1·009	1·001	1·001	1·001	1·001	1·001	1·001	1·001	1·001	1·001	1·001	1·001	1·001	
29	1983 Jan. 24(?)	R (mm)	26·9	30·6	44·6	72·6	115·9	165·0	238·3	247·3	303·0	349·0	530·3	666·5	721·4	Not conclusive
		R.P. (y)	1·009	1·001	1·001	1·001	1·001	1·01	1·009	1·001	1·001	1·001	1·001	1·001	1·001	
30	1983 Mar. 02	R (mm)	50·5	**127·1**	127·8	128·2	161·9	218·1	265·5	330·7	480·4	528·4	558·1	716·2	939·1	63.6
		R.P. (y)	1·01	**1·5**	1·3	1·1	1·09	1·1	1·009	1·001	1·03	1·001	1·001	1·001	1·05	
31	1985 Feb. 7	R (mm)	90·7	99·3	106·1	138·6	208·6	240·5	407·9	501·8	574·0	737·4	**854·9**	1082·4	1103·4	9.5
		R.P. (y)	1·4	1·2	1·1	1·1	1·3	1·2	1·4	1·5	1·1	1·3	**1·5**	1·5	1·2	
32	1986 Sep. 2	R (mm)	**161·6**	177·0	191·2	198·8	201·4	213·8	377·8	383·1	397·1	419·6	425·1	611·4	766·4	161.6
		R.P. (y)	**5·5**	3·4	3	1·8	1·2	1·07	1·2	1·07	1·001	1·001	1·001	1·001	1·005	
33	1996 Apr. 25 to 29	R (mm)	53·9	64·1	64·1	67·3	79·7	110·0	250·3	383·9	487·2	505·4	572·0	877·6	**1292·1**	8.6
		R.P. (y)	1·01	1·02	1·009	1·001	1·001	1·001	1·009	1·001	1·03	1·001	1·001	1·1	2	
34	1996 Dec. 14	R (mm)	**96·8**	97·8	97·8	149·2	193·1	198·1	241·5	282·6	486·1	514·6	551·0	702·8	742·0	96.8
		R.P. (y)	**1·4**	1·2	1·08	1·2	1·2	1·03	1·01	1·001	1·03	1·002	1·001	1·01	1·001	
35	1997 Sep. 10	R (mm)	182·2	**282·7**	282·9	283·6	327·0	349·2	428·8	455·7	462·4	484·1	488·5	753·8	1037·4	141.4
		R.P. (y)	12	**30**	15	6	4	2·4	1·5	1·2	1·02	1·001	1·001	1·01	1·1	
36	1997 Oct. 31	R (mm)	**220·0**	243·0	292·3	292·3	376·6	432·4	500·6	507·7	872·1	920·7	1000·8	1007·7	1208·6	220.0
		R.P. (y)	25	13	20	7	6	5	2·4	1·5	4	2	2·4	1·4	1·5	
37	1998 Jan. 25	R (mm)	94·6	136·6	136·6	145·5	224·4	277·2	437·3	608·8	892·1	1019·6	1386·7	1602·1	**1988·7**	13.3
		R.P. (y)	1·4	1·7	1·4	1·2	1·4	1·4	1·6	2·6	5	5	15	10	**20**	
38	1998 Oct. 1	R (mm)	**160·0**	160·4	160·4	162·0	164·2	237·8	246·4	326·8	339·3	353·8	364·4	418·2	550·4	160.0
		R.P. (y)	**5**	2·8	2	1·3	1·08	1·1	1·01	1·01	1·001	1·001	1·001	1·001	1·001	
39	2001 Dec.18	R (mm)	**138·2**	138·2	138·2	140·5	204·1	228·6	241·7	256·7	321·1	351·2	436·4	853·0	901·9	138.2
		R.P. (y)	**3·9**	1·8	1·4	1·2	1·3	1·1	1·01	1·001	1·001	1·001	1·001	1·09	1·03	
40	2002 Feb. 12	R (mm)	80·5	133·5	153·0	153·3	158·2	206·3	310·5	395·1	**1111·0**	1211·2	1219·7	1304·2	1455·9	18.5
		R.P. (y)	1·4	1·8	1·8	1·2	1·06	1·04	1·004	1·08	**20**	15	6	3	3	

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Table III. Calibrated antecedent rainfall (CAR) for 15 landslide events verified in Povoação County from 1976 to 2002

ID	Date	Daily rainfall (mm)	3 days (mm)	5 days (mm)	10 days (mm)	15 days (mm)	30 days (mm)
26	1980 Apr. 09	42·1	88·9	97·9	106·3	134·0	151·1
27	1981Feb. 18	40·6	58·4	58·6	86·1	86·2	90·1
28	1982 Oct. 7	34·2	30·8	32·5	37·7	37·8	41·8
29	1983 Jan. 24(?)	26·9	37·4	55·5	71·5	83·2	89·2
30	1983 Mar. 02	50·5	108·0	108·3	122·6	139·2	143·9
31	1985 Feb. 7	90·7	93·6	113·9	149·2	158·2	172·8
32	1986 Sep. 2	161·6	168·3	173·3	174·2	177·0	192·8
33	1996 Apr. 25 to 9	53·9	56·8	58·8	64·4	70·7	83·9
34	1996 Dec. 14	96·8	87·9	120·0	141·8	142·7	146·9
35	1997 Sep. 10	182·2	245·5	245·9	265·6	274·2	277·1
36	1997 Oct. 31	220·0	252·6	252·6	292·9	312·3	312·8
37	1998 Jan. 25	94·6	119·2	124·4	161·6	177·9	198·1
38	1998 Oct. 1	160·0	144·3	145·3	146·2	170·0	167·5
39	2001 Dec.18	138·2	124·4	125·8	154·5	160·0	162·0
40	2002 Feb. 12	80·5	129·6	129·8	131·7	145·7	154·6

one-third of the sea level pressure (SLP) variability in the Northern Hemisphere (Trigo *et al*., 2002). Recent work by two of the authors (Trigo *et al*., 2005; Zêzere *et al*., 2005) has found a significant control exerted by the NAO on the Portuguese mainland precipitation and over the recent geomorphological activity in the area around Lisbon.

There are several NAO indices in use (Hurrell *et al*., 2003) differing mainly on the location of their southern station. Historically, this station has been at Ponta Delgada in Azores (van Loon and Rogers, 1978), but more recently Lisbon (Hurrell, 1995) or Gibraltar (Jones *et al*., 1997; Trigo *et al*., 2002, 2004a) have also been widely used. Taking into account the location of our study area in this work we have opted for the Azores-based definition. Therefore, we have adopted the NAO index developed by the Climatic Research Unit (University of East Anglia, UK) defined on a monthly basis as the difference between the normalized surface pressures at Ponta Delgada and Stykkisholmur in Iceland. The NAO index for winter months presents a positive trend over the last 30 years; as a consequence its distribution is dominated by positive values, with monthly averages above zero (Hurrell, 1995; Jones *et al*., 1997). Therefore we decided to normalize (for the entire period of 1938–2001) the monthly NAO index so that each month has zero mean and standard deviation 1. The linear correlation coefficient between the extended winter precipitation (average November, December, January, February, March—NDJFM) at the EMLF rain gauge and the corresponding winter NAO index is −0·41 for the 63-year period (from 1938 to 2001) with available precipitation monthly data. While this value is statistically significant at the 5% level, it is considerably lower than what we have obtained for the Portuguese mainland area (Trigo *et al*., 2004a) and particularly for the Lisbon area where it is in the order of −0·65 (Trigo *et al*., 2005). The mean and standard deviation values of normalized monthly NAO index for months characterized by the occurrence of landslide events are −0·7 and 0·95, respectively. We have applied a two-tailed *t*-test (null hypothesis of equal means) and found that this average NAO value is significantly different from zero (at the 5% significance level). We should bear in mind that the monthly NAO indices used here possess zero average and unity variance as a consequence of the normalization procedure previously explained. Therefore, it is reasonable to conclude that months characterized by negative NAO index present a higher probability of landslide occurrence.

The atmospheric data used here corresponds to large-scale grid data retrieved from the National Centers for Environmental Prediction/National Center for Atmospheric Research (NCEP/NCAR) reanalysis dataset (Kistler *et al*., 2001). The assessment of the impact of NAO is performed using monthly average values of SLP, and precipitation rate (mm/day) for a 2·5° Lat. by 2·5° Long. grid. The grid data covers an Atlantic-European window that extends from 30°N to 70°N and from 60°W to 20°E, and our analysis is restricted to the period 1958–1997. Previous studies have shown that problems detected in reanalyses precipitation are considerably minimized when composites are used because bias are partially offset, and the obtained patterns are very similar to those attained with the Climate Research Unit (CRU) high-resolution grid dataset (Trigo *et al*., 2004a; Zêzere *et al*., 2005). SLP and precipitation rate anomaly fields for winter months characterized by high ($> 0{\cdot}5$) and low ($< -0{\cdot}5$) NAO index values were computed and they are shown in Figure 12(a) and (b), respectively. Differences of the SLP between winter months (NDJFM) with high and low NAO index (solid contour lines) can be seen in Figure 12(c) and show that the maximum differences enclose the Azores archipelago (south) and Iceland (north). The corresponding differences in precipitation rate (mm/day), between high and low NAO composites, are also represented in Figure 12(c), wherever those differences are statistically significant at the 5% level (colour scale). These significant precipitation differences are concentrated in the northern latitudes, between eastern Greenland and Norway, with maximum values

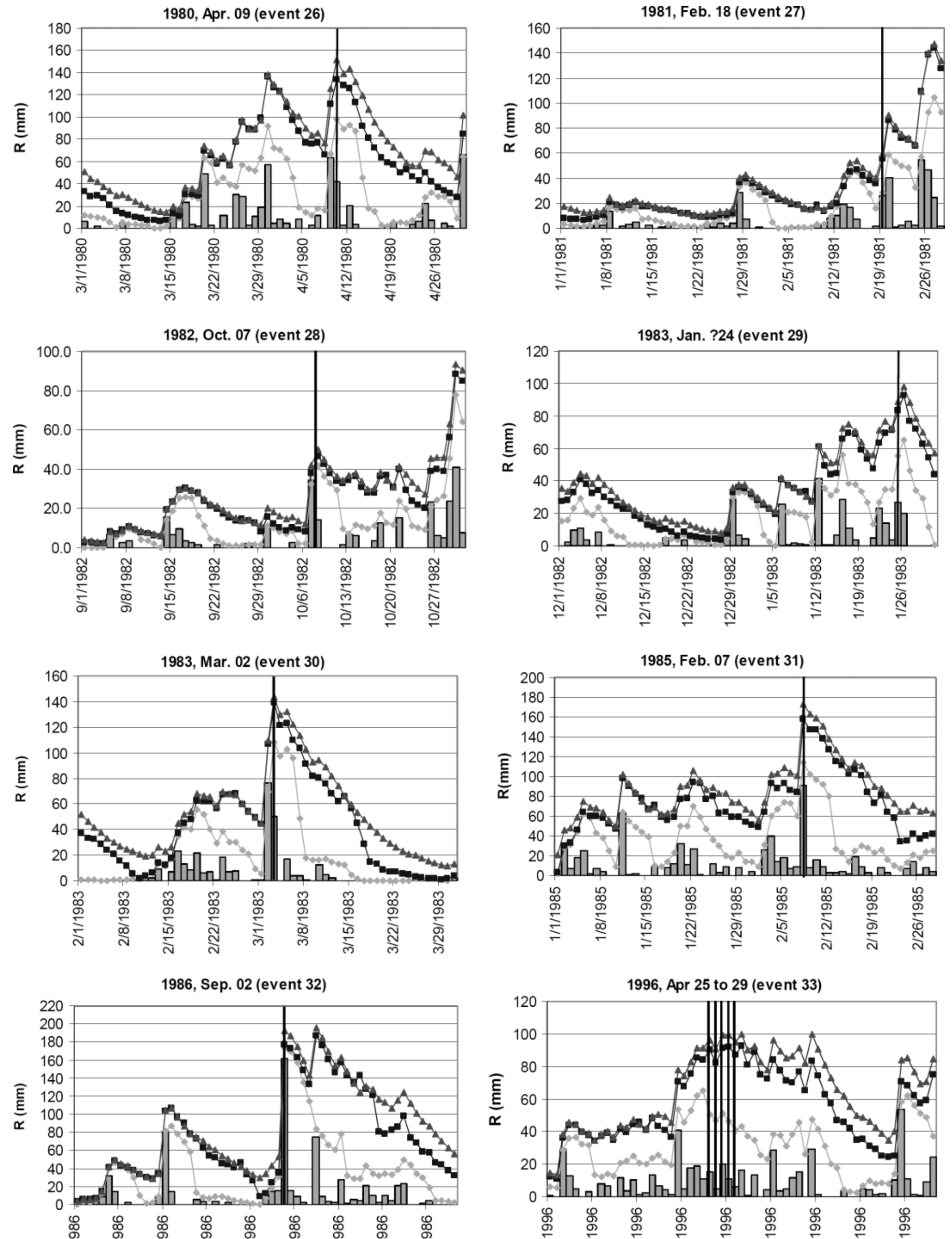

Figure 10. Daily rainfall and calibrated antecedent rainfall (CAR) in 3, 5, 10, 15 and 30 days for periods of landslide activity in Povoação County from 1976 to 2001. Legend: bars indicate daily rainfall; diamonds curve represents the 5-day CAR; squares curve represents the 15-day CAR; triangles curve represents the 30-day CAR and vertical lines indicate the landslide event date

located between Iceland and the United Kingdom. At lower latitudes, a strong band of negative differences extends from the eastern Canadian coast towards western Mediterranean, with maximum amplitude east and west of the Azores Islands.

The control exerted by NAO on the precipitation regimes is probably related to the corresponding changes in the North Atlantic storm paths that affect the western European coast (Ulbrich *et al*., 1999; Trigo *et al*., 2002). We have adapted the detection and tracking algorithm first developed by Trigo *et al*., (1999) for the Mediterranean basin. Both the detection and tracking schemes were performed using a 6-h SLP, available from NCEP/NCAR reanalysis on a $2{\cdot}5^{\circ} \times 2{\cdot}5^{\circ}$ grid. Again, these data cover the area from 30°N to 70°N and 60 °W to 20 °E, and the 40-year period from 1958 to 1997. Cyclones are identified as minima in SLP fields, fulfilling a set of conditions regarding the central pressure (less than 1020 hPa) and the pressure gradient, averaged over an area of about 11 002 km^2, has to be at least

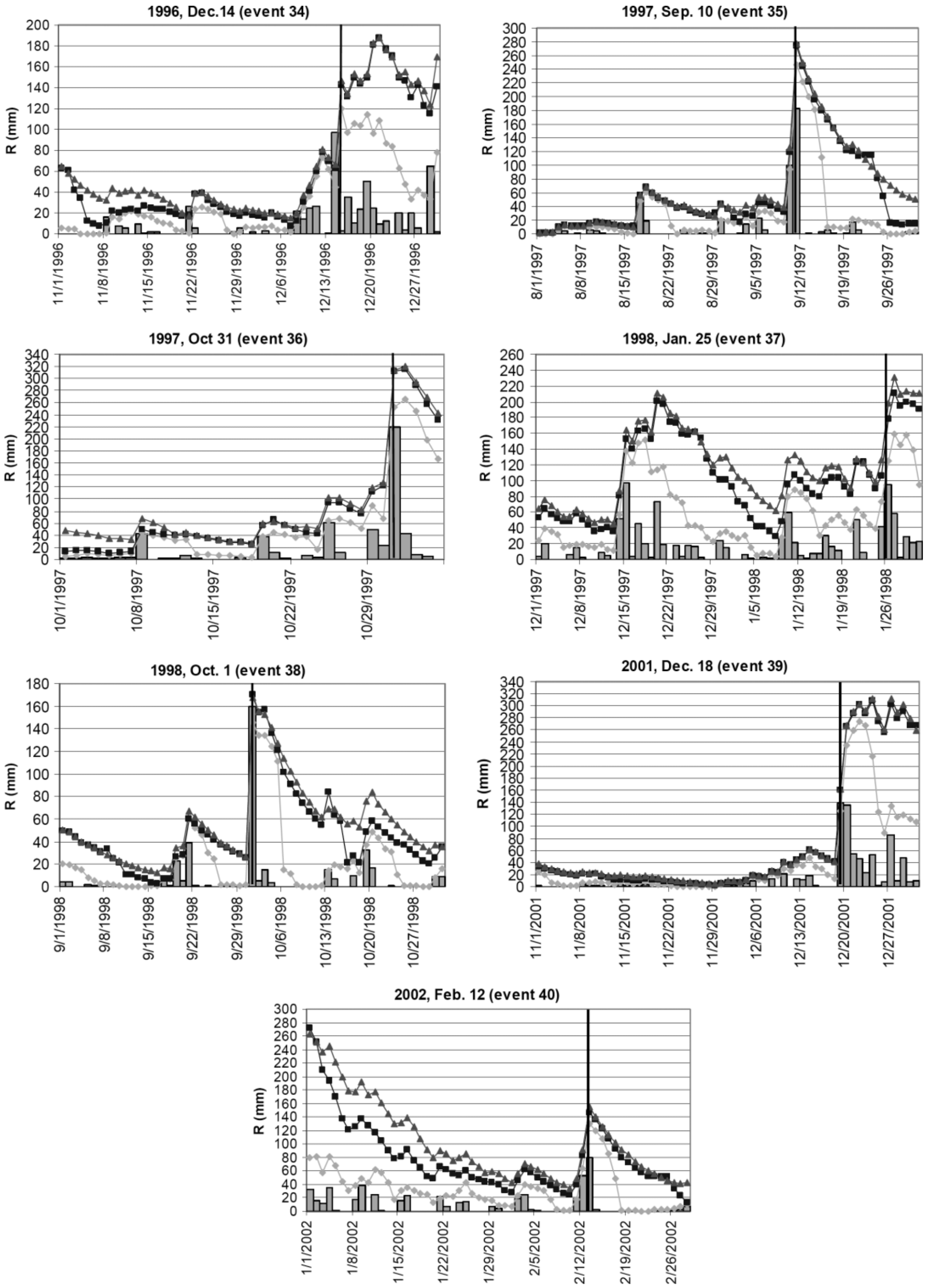

Figure 10. (*Continued*)

0·55 hPa/100 km. The tracking is based on a nearest neighbour search in consecutive charts, assuming that the speed of individual storms is less than 50 km/h in the westward direction, and 110 km/h in any other direction. Further details on the cyclone detecting and tracking method may be found in Trigo *et al*. (1999), Trigo *et al*. (2004b).

The anomalies of the average number of cyclones detected per winter, per $5^{\circ} \times 5^{\circ}$ cell normalized for 50°N, are plotted in Figure 13 for high and low NAO composites. For the high NAO composite a significant decrease in the number of cyclones between Newfoundland and the Iberian Peninsula is visible. On the contrary, for winter months characterized by positive NAO, the dominant cyclone paths are clustered between southern Greenland and the Scandinavian Peninsula. For the low NAO composite the obtained anomalies are basically the reversal of what has been described for the high NAO composite. It should be stressed that this type of tracking algorithm identifies and follows cyclone centres, and

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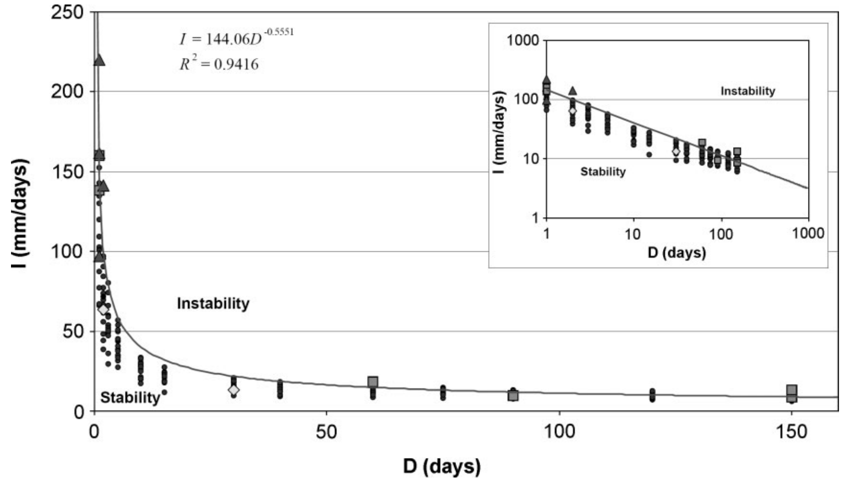

Figure 11. Regression line between critical rainfall intensity and corresponding event duration. In the right top corner the same data are represented in a log–log scale. Legend: triangles indicate disastrous landslide events; squares indicate severe landslide events and circles indicate minor landslide events

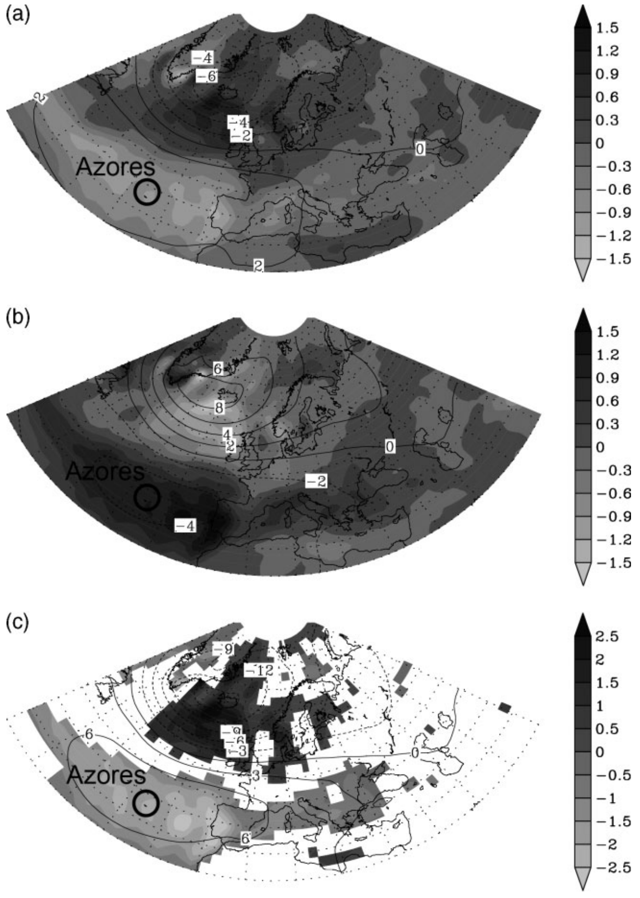

Figure 12. Precipitation rate anomaly fields (mm/day) for winter months with (a) high NAO index >0·5, (b) low NAO index $< -0{\cdot}5$ and (c) their difference (represented only if significant at the 5% level). Positive (solid) and negative (dashed) isolines of the sea level pressure anomaly field (hPa) are also represented (period 1958–1997). NAO index defined between Ponta Delgada (Azores) and Stykkisholmur

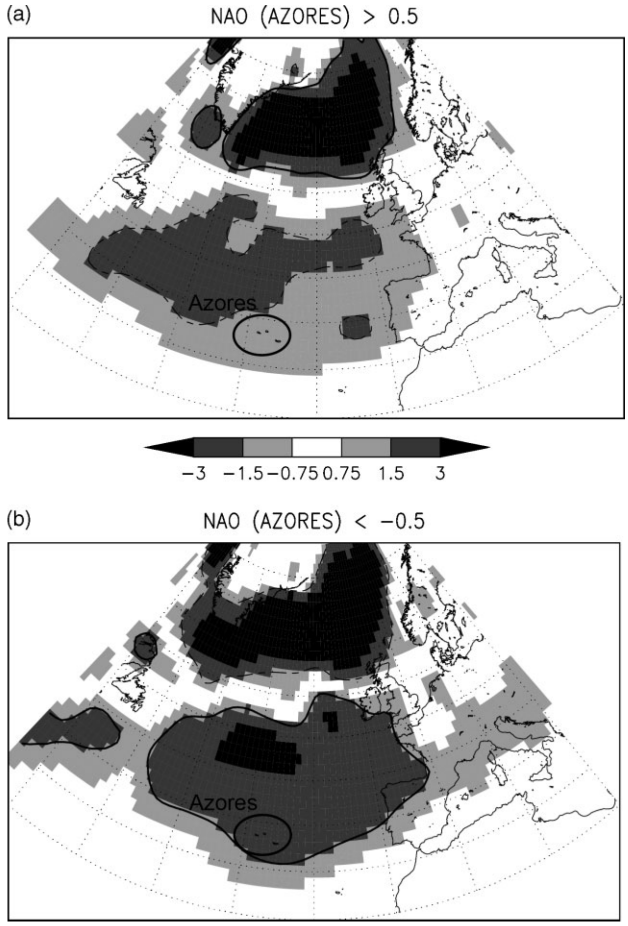

Figure 13. Number of cyclones per winter (NDJF), detected within boxes of 5° lon × 5° lat and normalized for 50°N, for (a) NAO >0·5 and, (b) NAO $< -0{\cdot}5$ (period 1958–1997). NAO index defined between Ponta Delgada (Azores) and Stykkisholmur

thus the anomalies described above (Figure 13(a) and (b)) also correspond to densities of storm centres. Therefore, it is expectable that the associated impact on precipitation extends further south of each main maximum/minimum shown, as a consequence of the cold and warm fronts that are usually present in these synoptic systems. This factor has to be taken into account when comparing the latitude of maximum impact of the NAO in precipitation rate anomalies at the latitude of Azores (Figure 12(a), (b)) which is located a few degrees south of the corresponding storm centres density anomalies shown in Figure 13.

This analysis is similar to the corresponding evaluation on the NAO impact on precipitation and storm density performed in a recent work that focused on landslide occurrence in the Lisbon area (Zêzere *et al*., 2005). We believe that the differences in patterns obtained for SLP and precipitation (Figure 12, Figure 12 of Zêzere *et al*., 2005) and storm tracks (Figure 13, Figure 16 of Zêzere *et al*., 2005) are mostly related to the fact that we have used the NAO index based in Ponta Delgada and not in Gibraltar.

We acknowledge that we have obtained apparently contrasting results in terms of NAO impact on local and large-scale precipitation. On one hand the precipitation rate anomalies in Figure 12 are of the same magnitude of those obtained in Zêzere *et al*. (2005, Figure 12); on the other hand the correlation between local winter precipitation and the NAO index was −0·65 for Lisbon and is 'only' −0·41 for the EMLF station in this study. We believe that the explanation for this apparent contradiction lies with the considerable higher average precipitation values registered in the mid-Atlantic area (including the EMLF station, with an average precipitation close to 2000 mm per year), while Lisbon registers an average precipitation of less than 800 mm per year. Therefore, the relative importance of precipitation rate anomalies depicted in Figure 12 over the archipelago of Azores is considerably less relevant then the corresponding anomalous precipitation rate patterns obtained over western Iberia (Figure 12 of Zêzere *et al*., 2005).

SUMMARY AND CONCLUSIONS

Historical accounts and recent observations show that rainfall-induced landslides are very frequent in Povoação County.

The analysis presented in this work has only considered a single causal factor for landslide occurrence. Other factors include predominantly human intervention and seismicity; however, these are of minor importance when compared to the dominance of rainfall both as a preparatory and trigger mechanism.

In our work we use a statistical and probabilistic approach of rainfall extreme values using Gumbel asymptotic extreme values distribution function and different cumulative rainfall methods based on daily data, in order to evaluate rainfall patterns and critical rainfall values for landslide occurrence in Povoação County. These findings should be tempered by the fact that rainfall–landslide correlations were based on the assumption that rainfall was uniformly distributed over the entire area (based on one meteorological station) and the daily rainfall time series analysed includes only 26 years. This investigation cannot account for complex relationships between landslides and precipitation and therefore ignores factors that determine slope failure. Despite these constraints we are confident that a strong relationship has been found between the rainfall patterns and the occurrence of shallow slope movements in Povoação County.

Assessment of empirical rainfall thresholds provides no causal mechanisms for slope failures. Nevertheless, results from the statistical rainfall analyses are consistent with the different hydrological triggering conditions related with two different types of landslides. Shallow translational soil slips are triggered by the rapid infiltration of water into the thin layer of soil material. The temporary rise of the pore water pressure as well as the loss of apparent soil cohesion resulting from soil saturation are responsible for a critical reduction of the soil shear resistance and resultant failure (Gostelow, 1991; Iverson, 2000). For this area these hydrological conditions are marked by generalized landsliding activity triggered by short periods of rainfall accumulation (1–3 days), characterized by high average intensity (between 78 and 144 mm/day). Deep-seated landslides, normally much more localized in the study area, involve rocks and soils that yield small hydraulic diffusivities. They are triggered by the reduction of shear strength of affected soil and rocks, linked with the steady rise of the groundwater level resulting from long-term precipitation periods (from 1 to 5 months, like the event ID33) with a lower intensity (between 9 and 22 mm/day).

Some important landslide events (e.g. event ID37) seem to be related to a two-stage pattern of precipitation: (1) a preparatory rainy period, 15 days before the occurrences, when slopes are destabilized and conditioned for failure, followed by (2) a more intense and short rainfall episode (1 or 2 days) that triggers the landslide. Moreover, it is possible to conclude that there is a complete constriction of disastrous landslide events to exceptional high-intensity rainfall occurrences, always higher than 97 mm/day, which happen very close to the day of the event.

Despite the extreme nature of many of the studied rainfall episodes that triggered landsliding activity, they do not have very high return period values. Most of them are very frequent and all of them can occur several times in a lifetime. This important feature cannot be ignored and has to be taken into account supporting future land use planning decisions.

The NAO exerts a discernible control on the rainfall regime of the Azores archipelago, which is related to the corresponding changes in the North Atlantic storm paths. In this work, we have adopted the NAO index, defined as the difference between the normalized surface pressure at Ponta Delgada and Stykkisholmur, on a monthly basis. A coefficient value of −0·41 was found for the linear correlation between winter (NDJFM) precipitation in the Lagoa das Furnas rain gauge and the corresponding winter NAO index, this value being statistically significant at the 5% level. The average NAO index value, for months characterized by the occurrence of landslide events, was found to be −0·7, which is significantly different from zero (at the 5% significance level). While the NAO seems to play a relevant role in determining the magnitude of winter precipitation by steering the path of many atmospheric disturbances, its direct link to landslide activity in the island is not as clear as it was found in previous studies for the Lisbon area.

With this study we intend to improve the knowledge of rainfall patterns and critical values for landslide activity. The obtained results should be tested and improved in the future, in order to be used for the development of warning systems for landslide risk mitigation, providing an important background for land use and emergency planning.

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